METRIC
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MILITARY SPECIFICATION

WORLD MAGNETIC MODEL (WMM)

This specification is approved for use by all Departments and Agencies of the Department of Defense

1. SCOPE

1.1 Scope. These specifications are designed to provide guidelines for the preparation and use of the spherical harmonic World Magnetic Model (WMM) and the charts and grid tables derived from the model. These specifications also provide guidelines for the preparation and use of computer programs and subroutines, distributed under the name GEOMAG, that compute from the model magnetic field parameters such as declination *(D)*, inclination *(I)*, total intensity *(F)*, horizontal intensity *(H)*, vertical component *(Z)*, and grid variation *(G)* at any desired point below, on, or above the Earth's surface at any time during the 5-year lifetime of the model.

1.2 Purpose. The purpose of this document is to specify the WMM and the Defense Mapping Agency (DMA) products that are derived from the model. This document also specifies the accuracy and limitations of the model.

1.3 Security.

1.3.1 Security classification of specification. This military specification is UNCLASSIFIED.

1.3.2 Security classification of product. The WMM spherical harmonic coefficients, related computer software, charts, grids and other products derived from the model are UNCLASSIFIED.

Beneficial comments (recommendations, additions, deletions) and any pertinent data which may be of use in improving this document should be addressed to: Director, Defense Mapping Agency, ATTN: PR, ST A-13, 8613 Lee Highway, Fairfax, VA 22031-2137 by using the Standardization Document Improvement Proposal (DD Form 1426) appearing at the end of this document or by letter.

AMSC B6924

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DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

2. APPLICABLE DOCUMENTS

2.1 Government documents.

2.1.1 Specifications, standards, and handbooks. The following specifications, standards, and handbooks form a part of this document to the extent specified herein. Unless otherwise specified, the issues of these documents are those listed in the current Department of Defense Index of Specifications and Standards (DODISS) and the supplement thereto, cited in the solicitation (see 6.2).

MILITARY STANDARDS

MIL-STD-600010	Military Standard for DMA Stock Number/Bar Coding

(Unless otherwise indicated, copies of federal and military specifications, standards, and handbooks are available from the Standardization Documents Order Desk, Bldg. 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094).

2.1.2 Other government documents drawings and publications. The following other Government documents, drawings and publications form a part of this document to the extent specified herein. Unless otherwise specified, the issues are those cited in the solicitation.

a. DMAINST 8000.1: Geodetic and Geophysical Sign Conventions and Fundamental Constants.

b. DMAINST 8000.2: DoD Mapping, Charting, and Geodesy (MC&G) Libraries.

(Copies of DMAINST 8000.1 and DMAINST 8000.2, are available from the Defense Mapping Agency, ATTN: IM, ST A-28613 Lee Highway, Fairfax, VA 22031-2137.)

c. DMA Technical Report "Department of Defense World Geodetic System 1984; Its Definition and Relationships with Local Geodetic Systems", (DMA TR 8350.2).

d. North/South Polar Stereographic Projections of Magnetic Declination *(D)* and Grid Variation *(G)* (DMA Stock #WOBZC43).

e. World Mercator and North/South Polar Stereographic Projections of Magnetic Inclination *(I)* (DMA Stock #WOXZC30).

f. World Mercator and North/South Polar Stereographic Projections of Horizontal Magnetic Intensity *(H)* (DMA Stock #WOXZC33).

g. World Mercator Projection of Magnetic Declination *(D)*

(DMA Stock #WOBZC42).

h. World Mercator Projection of Total Magnetic Intensity *(F)* (DMA Stock #WOXZC39).

i. World Mercator Projection of Vertical Magnetic Component *(Z)* (DMA Stock #WOXZC36).

(Copies of DMA TR 8350.2, DMA Stock #WOBZC43, DMA Stock #WOXZC30, DMA Stock #WOXZC33, DMA Stock #WOBZC42, DMA Stock #WOXZC39, DMA Stock #WOXZC36 are available, from the Defense Mapping Agency Combat Support Center, ATTN: PMSR, ST D-17, 6001 MacArthur Blvd., Bethesda, MD 20816-5001).

j. NAVOCEANO Brochure "The Magnetic Variation Algorithm (GEOMAG) and the 1990 World Magnetic Model".

k. NAVOCEANO Technical Report "The Joint US/UK 1990 Epoch World Magnetic Model", (NAVOCEANO TR 304).

(Copies of NAVOCEANO GEOMAG Brochure and NAVOCEANO TR 304 are available from the Commanding Officer, U.S. Naval Oceanographic Office, Stennis Space Center, Mississippi 39522-5001).

l. STANAG 4294, NAVSTAR Global Positioning System (GPS) System Characteristics, Draft Issue H, Appendix 6 to Annex A.

(Copies of STANAGs are available from the Standardization Documents Order Desk, Bldg. 4-D, 700 Robbins Avenue, Philadelphia, PA 19111-5094.)

2.2 Non-Government publications. The following documents form a part of this document to the extent specified herein. Unless otherwise specified, the issues of the documents which are DoD adopted are those listed in the issue of the DODISS cited in the solicitation. Unless otherwise specified, the issues of documents not listed in the DODISS are the issues of the documents cited in the solicitation (see 6.2).

a. Cain, Joseph, C., et al.; A Proposed Model for the International Geomagnetic Reference Field 1965, Journal of Geomagnetism and Geoelectricity, Vol. 19, No. 4, pp. 335-355, 1967 (see appendix).

b. Quinn, John M., David J. Kerridge and David R. Barraclough; World Magnetic Charts for 1985 - spherical harmonic models of the geomagnetic field and its secular variation, Geophys. J.R. Astr. Soc. Vol. 87, pp. 1143-1157, 1986.

c. Zmuda, Alfred J.; World Magnetic Survey 1957-1969, International Association of Geomagnetism and Aeronomy (IAGA) Bulletin #28, pp. 186-188, 1971.

(Non-Government standards, and other publications are normally available from the organizations that prepare or distribute the documents. These documents also may be available in or through libraries or other informational services.)

2.3 Order of precedence. In the event of a conflict between the text of this document and the references cited herein (except for related associated detail specifications, specification sheets, or MS standards), the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption is obtained.

3. REQUIREMENTS

3.1 First article. When specified (see 6.2), a sample shall be subjected to first article inspection (see 6.3) in accordance with 4.3.

3.2 Magnetic component accuracies.

a. North *(X)* component magnetic field values generated by the WMM and the GEOMAG software will be in error less than 140 nanoteslas (nT) relative to that observed at sea level in the Root Mean Square (RMS) sense worldwide at any time over the entire 5-year lifetime of each model. The requirement for *(X)* is derived from the requirement for *(H)*.

b. East *(Y)* component magnetic field values generated by the WMM and the GEOMAG software will be in error less than 140 nT relative to that observed at sea level in a RMS sense worldwide at any time over the entire 5-year lifetime of each model. The requirement for *(Y)* is derived from the requirement for *(H)*.

c. Vertical *(Z)* component magnetic field values generated by the WMM and the GEOMAG software will be in error less than 200 nT (RMS) relative to that observed at sea level worldwide at any time over the entire 5-year lifetime of each model.

d. Horizontal *(H)* component magnetic field values generated by the WMM and the GEOMAG software will be in error less than 200 nT (RMS) relative to that observed at sea level worldwide at any time over the entire 5-year lifetime of each model.

e. Total Intensity *(F)* component magnetic field values generated by the WMM and the GEOMAG software will be in error less than 280 nT (RMS) relative to that observed at sea level worldwide at any time during the entire 5-year lifetime of each model. The requirement for *(F)* is derived from the *(H)* and *(Z)* requirements.

f. Declination *(D)* component magnetic field values generated by the WMM and the GEOMAG software will be in error less than 1 degree (RMS) relative to that observed at sea level worldwide at any time during the entire 5-year lifetime of each model. The east component magnetic variation sign is "+". The westerly component magnetic variation sign is "-".

g. Inclination *(I)* component magnetic field values generated by the WMM and the GEOMAG software will be in error less than 1 degree (RMS) relative to that observed at sea level worldwide at any time during the entire 5-year lifetime of each model. The requirement for *(I)* is based on the *(H)* and *(Z)* requirements.

h. Grid Variation *(G)* component magnetic field values generated by the WMM and the GEOMAG software will be in error less than 1.0 degrees (RMS) relative to that observed at sea level in the polar regions only, above 55° North and below 55° South at any time during the entire 5-year lifetime of each model.

i. RMS component errors specified in items (a) through (h) above are to be uniformly distributed over the globe such that on a regional basis, each magnetic parameter has a Gaussian error distribution with respect to its global RMS error.

3.3 Datums.

3.3.1 Vertical and horizontal datum. The datum used by the WMM is the World Geodetic System (WGS) 1984. The reference ellipsoid is published in DMA Technical Report "Department of Defense World Geodetic System 1984; Its Definition and Relationships with Local Geodetic Systems" (DMA TR 8350.2).

3.3.2 Time datum. Each edition of the WMM shall have a specified base year (epoch). Unless otherwise specified or approved, each edition of the WMM will have a valid operational service life limited to five (5) years forward from that time.

3.4 Product description.

3.4.1 World Magnetic Model (WMM). The WMM is a spherical harmonic model of the Earth's main (core generated) magnetic field and its secular (slow temporal) change. The main field portion is to degree and order 12 and consists of 168 Schmidt-normalized spherical harmonic coefficients. The secular change field is also specified to degree and order 12 and consists also of 168 coefficients. Currently, however, the coefficients above degree 8 of the secular variation model are set to zero. This is due to the current lack of data to generate this portion of the model. This model characterizes only the long wavelength (>3300 km) portion of the earth's magnetic field. Medium and short wavelength features associated with the Earth's magnetic crust are not represented. A much higher degree and order model would be required to model these features. Also not included in this model are seasonal, daily and other temporal fluctuations of the Earth's magnetic field that are driven by the Solar Wind and modulated by magnetospheric and ionospheric current systems such as the Ring Current, the North and South Polar auroral Electroject Currents and the Equatorial Electroject Current. Magnetic fields generated by these current systems can be quite pronounced particularly in regions of high magnetic latitudes and during periods of high Solar activity.. The WMM, nevertheless, does represent approximately 95% of the earth's magnetic field. The model is updated at 5-year intervals (i.e., 1990, 1995, 2000, etc.) and is referred to by its epoch date (e.g., WMM-90, WMM-95, etc.). WMM-90 is valid between 1990.0 and 1995.0, WMM-95 will be valid from 1995.0 to 2000.0, etc. The world magnetic charts referenced in 2.1.2 d-i are generated directly from the WMM and are indicative of the spatial resolution of the model. Mathematical details of the model are given in the appendix.

3.4.2 GEOMAG computer software. GEOMAG is a computer software FORTRAN subroutine or BASIC program which uses the WMM to compute the Earth's magnetic declination *(D)*, inclination *(I)*, total magnetic intensity *(F)*, and grid variation *(G)* at any geographic position around the world at any depth/altitude between -100 km/+1000 km relative to sea level and at any time during the 5-year lifetime of the model. All other magnetic field components such as the north *(X)*, the east *(Y)*, the horizontal intensity *(H)* and vertical component *(Z)* can be computed by the user from the three basic magnetic components *(D)*, *(I)* and *(F)* computed via GEOMAG. This is done by using the simple mathematical relationships contained in the NAVOCEANO brochure that accompanies the GEOMAG subroutine. The grid variation *(G)* is computed in the polar regions only (i.e., above 55° North and below 55° South) and is referenced to Grid North of a Polar Stereographic Projection. Input parameters (i.e., geodetic latitude, geodetic longitude, and geodetic altitude) and output magnetic field parameters (i.e., *D*, *I*, *F*, and *G*) are referred to the WGS-84 ellipsoid. GEOMAG performs the necessary coordinate transformations and vector rotations between the geodetic and spherical coordinates. Because the declination *(D)* is frequently referred to as the magnetic variation, the GEOMAG software is also distributed under the name MAGVAR. Details of the computer software are given in the APPENDIX. The GEOMAG software is available in three different languages: FORTRAN (two versions), BASIC, and C. One FORTRAN version has the model coefficients imbedded in the Algorithm as DATA statements, while the other reads the model coefficients from an external file. Both versions are intended to be easily inserted into user developed code. A sample driver is supplied with these versions of GEOMAG as an example of the usage and calling sequence of the GEOMAG subroutine and its entry points. The BASIC and C versions of GEOMAG are stand-alone programs which read the model coefficients from an external file.

3.4.3 World magnetic charts. DMA publishes small scale contour charts of several magnetic components and their secular variations based on the WMM. In years divisible by 5, DMA publishes charts for the *D*, *I*, *F*, *Z*, *H*, and *G* components. In years divisible by 10, DMA publishes only the *D* and *G* components. The specific charts are as follows:

a. Inclination *(I)* (DMA STOCK #WOXYC30) Mercator projection on front, North and South polar Stereographic projections on the back.

b. Horizontal Intensity *(H)* (DMA STOCK #WOXYC33) Mercator projection on front, North and South polar Stereographic projections on the back.

c. Vertical component *(Z)* (DMA STOCK #WOXZC36) Mercator projection on front only.

d. Total Intensity *(F)* (DMA STOCK #WOXZC39) Mercator projection on front only.

e. Declination *(D)*, also called Magnetic Variation, (DMA STOCK #WOBZC42) Mercator projection on front only.

f. Declination *(D)*, also called Magnetic Variation, North and South polar Stereographic projections on front and Grid Variation *(G)*, North and South polar Stereographic projections on the back (DMA STOCK #WOBZC43). On each of these charts, the main field component contours are colored purple or magenta, while the secular variation contours of each magnetic component are colored blue.

3.4.4 Units. The Total Intensity *(F)*, Horizontal Intensity *(H)*, North *(X)* component, the East *(Y)* component and the Vertical *(Z)* component magnetic field values are expressed in nanoteslas (nT) while the secular variation of these components are expressed in nanoteslas per year (nT/yr). The Declination *(D)*, Inclination *(I)* and Grid Variation *(G)* are expressed in decimal degrees. The secular variation of these magnetic parameters are expressed in minutes of arc per year (min/yr). The main field WMM coefficients are expressed in nanoteslas (nT). The secular variation WMM coefficients are expressed in nanoteslas per year (nT/yr). The geodetic latitude and longitude are expressed in decimal degrees, while altitude is expressed in kilometers (km). Time is referenced in decimal years (e.g., 15 May 1991 is 1991.371).

3.4.5 Sign conventions. The Earth's magnetic field components are referenced to a local geodetic coordinate system, which is oriented such that the positive *X*-axis points North, the positive *Y*-axis points East, and the positive *Z*-axis points vertically downward. Consequently, the negative *X*-axis points South, the negative *Y*-axis points West, and the negative *Z*-axis points vertically upwards, away from the Earth. Latitude ranges between $-90°$ to $+90°$, while longitude ranges from $-180°$ to $+180°$.

3.4.6 Exchange medium. The exchange media for the WMM consists of the following:

a. Low density (360 Kb), 5-1/4 inch floppy diskettes containing the WMM model coefficients, the GEOMAG software in either FORTRAN 77 or Microsoft BASIC and test values and an accompanying user text file. Software is IBM-PC compatible.

b. High density (1.44 Mb), 3-1/2 inch diskettes containing the WMM model coefficients, the GEOMAG software in either FORTRAN 77 or Microsoft BASIC and test values and an accompanying user text file. Software is IBM-PC compatible.

c. 9-Track 6250 BPI magnetic tape containing the WMM coefficients, the GEOMAG software in FORTRAN 77 and test values.

d. Small scale paper charts published by DMA of the *D*, *I*, *F*, *H*, *Z*, and *G* magnetic components and their secular variations.

e. NAVOCEANO Technical Report containing a complete mathematical description of the WMM, the method of its derivation, the computational method of the GEOMAG algorithm, grid values of each magnetic component and their secular variations around the world at the model's base epoch and world contour charts of these components also at the base epoch of the model.

3.5 Labeling. Each diskette or magnetic tape shall be ASCII formatted and labeled to indicate the magnetic model epoch, and compiler type and version (e.g., Microsoft FORTRAN Version 4.5)

3.6 User instructions. Each diskette or magnetic tape will be accompanied by user instructions regarding the operation of the GEOMAG algorithm. Additionally, each diskette or magnetic tape will be distributed with a brochure which describes the WMM and the GEOMAG algorithm along with the appropriate uses and limitations of the model.

3.7 Bar code and DMA stock number.

a. Each WMM product shall have a unique stock number and bar code identification which conforms to the requirement of the DMA Automated Distribution Management System (DADMS) and MIL-STD-600010.

b. The identification shall consist of the words "DMA Stock No." followed by an alphanumeric designation not to exceed 15 characters.

c. The Human Readable Information (HRI) portion of the bar code will be Swiss 742 type (or equivalent) and is printed in black.

3.8 Publishing and copyright note. The DMAHTC Publishing

Note identifies DMAHTC as the publishing authority, and identifies the product as copyrighted material. The note below is shown on each product in black (SPC-58600).

Prepared and Published by the
DEFENSE MAPPING AGENCY HYDROGRAPHIC/TOPOGRAPHIC CENTER
Bethesda, Maryland

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4. QUALITY ASSURANCE

4.1 Responsibility for inspection. Unless otherwise specified, the U.S. Naval Oceanographic Office (NAVOCEANO), is responsible for the performance of all inspections required (examinations and tests) as specified herein. The Government reserves the right to perform any of the inspections set forth in this specification, where such inspections are deemed necessary, to ensure supplies and services conform to prescribed requirements.

4.1.1 Responsibility for compliance. Any products produced to this specification shall meet all requirements of paragraphs 3 and 5. All inspections set forth in this specification shall become a part of NAVOCEANO's overall inspection system or quality program. The absence of any inspection requirements in the specification shall not relieve any contractor of the responsibility of insuring that all products submitted to the government for acceptance comply with all requirements of the contract. Sampling inspection, as a part of production operations, is an acceptable practice to ascertain conformance to requirements; however, this does not authorize submission of known defective products, either indicated or actual, nor does it commit the government to accept defective products.

4.2 Tests. NAVOCEANO will include a test data set with the program which can be used to verify that the program gives the correct results.

5. PACKAGING

5.1 Packaging. Packaging for the exchange medium (see 3.4.6) shall be level C (see 6.2) unless otherwise specified. This packaging provides minimum protection, and it is needed to protect materiel under known favorable conditions. The following criteria determine the requirements for this degree of protection:

a. Use or consumption of the item at the first destination.

b. Shock, vibration, and static loading during the limited transportation cycle.

c. Favorable warehouse environment for a maximum of 18 months.

d. Effects of environmental exposure during shipment and intransit delays.

e. Stacking and supporting superimposed loads during shipment and temporary storage.

5.2 Marking. In addition to any special markings required by the contract or order, markings shall be in accordance with requirements of MIL-STD-129 for military levels of protection.

6. NOTES

This section contains information of a general or explanatory nature that may be helpful, but is not mandatory.

6.1 Intended use. The World Magnetic Model is intended for use in the public, private and government domains for such purposes as a general aid to navigation and attitude determination, as an aid in various military applications such as target acquisition, as a scientific research tool, and as an explorational geophysics and mineral resource evaluation tool.

6.1.1 WMM data. The data used to construct the WMM is collected by a wide variety of public and private agencies of domestic and foreign origin which adhere to the scientific standards and nomenclatures adopted by the International Association of Geomagnetism and Aeronomy, IAGA, and the International Union of Geodesy and Geophysics, IUGG.

6.2 Acquisition requirements. Acquisition documents must specify the following:

a. Title, number, and date of this specification.

b. Issue of DODISS to be cited in the solicitation, and if required, the specific issue of individual documents referenced (see 2.1.1 and 2.2).

c. When a first article is required (see 3.1, and 6.3).

d. Level of packaging (see 5.1).

6.3 First article. When a first article is required, it shall be inspected and approved under appropriate provisions of FAR 52.209. The contracting officer shall specify the appropriate type of first article and the number of units to be furnished. The contracting officer shall also include specific instructions in acquisition documents regarding arrangements for selection, inspection, and approval of the first article.

6.4 International standardization agreements.

Certain provisions of this specification may be subject to international standardization agreements. When amendment, revision, or cancellation of this specification is proposed that will modify the international agreement concerned, the preparing activity will take appropriate action through international standardization channels, including departmental standardization offices, to change the agreement or make other appropriate accommodations.

6.4.1 International Standardization Agreements (STANAGs).

STANAG 4294, NAVSTAR Global Positioning System (GPS) System Characteristics.

6.4.2 Quadripartite Standardization Agreements (QSTAGs). This section is not applicable to this specification.

6.4.3 Air Standardization Coordinating Committee Agreements (ASCC). This section is not applicable to this specification.

6.4.4 International MC&G Agreements. This section is not applicable to this specification.

6.4.5 Executive Orders. This section is not applicable to this specification.

6.4.6 Interagency Agreements. This section is not applicable to this specification.

6.4.7 Other Documentation. This section is not applicable to this specification.

6.5 Subject term (keyword) listing.

GEOMAG algorithm
Local geodetic coordinate
Nanoteslas
Spherical harmonic model

6.6 Abbreviations.

D - Declination (magnetic variation)
DADMS - DMA Automated Distribution Management System
DMAHTC - Defense Mapping Agency Hydrographic/Topographic Center
F - Total intensity
G - Grid variation
GEOMAG - Geo-Magnetic software
GPS - Global Positioning System

H- Horizontal intensity
I - Inclination component
IAGA - International Association of Geomagnetism and Aeronomy
IUGG - international Union of Geodesy and Geophysics
NAVOCEANO - Naval Oceanographic Office
nT - nanoteslas
RMS - Root mean Square
WGS - World Geodetic System
WMM - World Magnetic Model
X - North component magnetic field value
Y - East component magnetic field value
Z - Vertical component

APPENDIX

PRODUCT DESCRIPTION

10. SCOPE

10.1 Scope. This appendix is a mandatory part of the specification. The information contained herein is intended for compliance.

20. APPLICABLE DOCUMENTS

This section is not applicable to this appendix.

30. PRODUCT DESCRIPTION

30.1 Model description. The Earth's magnetic field, as measured by a magnetic sensor on or above the Earth's surface, is actually a composite of several magnetic fields generated by a variety of sources, which are superimposed on each other and which interact with each other. The most important of these geomagnetic sources are as follows:

a. the Earth's fluid outer core;
b. the Earth's crust/upper mantle;
c. the ionosphere and,
d. the magnetosphere

The magnetic variation algorithm (GEOMAG) is based on a spherical harmonic expansion of the Earth's main (core-generated) magnetic field and the secular variation of the Earth's core-generated field, the coefficients of which comprise the WMM. The 1990 Epoch Coefficient set was produced jointly by the Geopotential Division of the U.S. Naval Oceanographic Office (NAVOCEANO) and the Geomagnetism Research Unit of the British Geological Survey (BGS), an agent of the British Hydrographic department. The model is distributed by NAVOCEANO's DOD Geomagnetic data Library, which is operated on behalf of the defense Mapping Agency (DMA) in accordance with DMA instructions 8000.1 and 8000.2. The WMMs are usually produced at 5-year intervals and are composed of two parts: a main field model, which describes the Earth's main magnetic field at some base epoch, and a secular variation model, which forecasts the slow temporal variations in the main geomagnetic field from the base epoch to a maximum of 5 years beyond the base epoch. For example, the base epoch of the WMM-90 magnetic field model is 1990.0. This Model is a valid forecast only between 1990.0 and 1995.0 and will subsequently be replaced at 1995.0 by the WMM-95 magnetic field model.

30.2 Model limitations. It is extremely important to recognize that the WMM series of geomagnetic models and the charts produced from these models characterize only that portion of the Earth's magnetic field which is generated by the Earth's fluid outer core. The portions of the geomagnetic field generated by the Earth's crust, mantle, ionosphere, and magnetosphere are not represented in these models. Consequently, a magnetic sensor such as a compass or magnetometer may observe spatial and temporal magnetic anomalies when referenced to the appropriate WMM. In particular, certain local, regional, and temporal magnetic declination anomalies can exceed 10 degrees. Anomalies of this magnitude are not common, but they do exist. Declination anomalies on the order of 3 or 4 degrees are not uncommon, but are of small (<50 km) spatial extent and are relatively isolated. On land, spatial anomalies are produced by basaltic intrusions of volcanic origin, ore deposits, ground which has been struck by lightning, geological faults, and cultural features such as trains, planes, tanks, railroad tracks, power lines, etc. In ocean areas, spatial anomalies are produced by continental margins, seamounts, oceanic ridges, trenches and fault zones, and ships and submarines. Temporal anomalies in either ocean or land areas can last from a few minutes to several days and are produced by ionospheric and magnetospheric processes which are driven by the solar wind. Magnetic storms in particular can cause severe and persistent magnetic anomalies. Even in periods of quiet solar activity, significant spatial and temporal magnetic anomalies are found in the polar and equatorial regions of the Earth where magnetic fields produced by ionospheric current systems such as the auroral electrojets and the equatorial electrojet are always present. Most of the possible sources of magnetic anomalies are comparatively isolated in either space or time. Therefore, from a global perspective, the root-mean-square (RMS), declination (DEC), and inclination (DIP) errors at sea level of the WMM are estimated to be less than 1.0 degree worldwide at the Earth's surface over the entire 5-year life of a particular model. Also, the RMS errors at sea level of the horizontal intensity *(H)* and the vertical magnetic component *(Z)* of the WMM worldwide are estimated to be less than 200 nanoteslas (nT) over the entire 5-year life of the models.

30.3 The mathematical model. The Earth's magnetic field has associated with it a geomagnetic potential $V(r,\theta,\phi,\tau)$, which can be expressed in spherical coordinates in terms of a spherical harmonic expansion of the following form:

$$V(r,\theta,\phi,\tau) = R_E \sum_{n=1}^{N} \left(\frac{R_E}{r}\right)^{n+1} \sum_{m=0}^{n} \left\{ g_{nm}(\tau)\cos m\phi + h_{nm}(\tau)\sin m\phi \right\} P_n^m(\theta)$$

where the spherical coordinates (r,θ,ϕ) correspond to the radius from the center of the Earth, the colatitude (i.e., 90° - latitude) and the longitude. R_E is the mean radius of the Earth, $g_{nm}(\tau)$ and $h_{nm}(\tau)$ are referred to as the Gauss coefficients at time

τ, where τ is the time in years (e.g., 1987.312). $P_n^m(\theta)$ represents a particular associated Legendre polynomial of degree n and order m. These polynomials are functions of the colatitude θ. The Gauss coefficients are slowly varying functions of time and are expressed in the form:

$$g_{nm}(\tau) = g_{nm}(T_{EPOCH}) + \dot{g}_{nm}(\tau - T_{EPOCH})$$

$$h_{nm}(\tau) = h_{nm}(T_{EPOCH}) + \dot{h}_{nm}(\tau - T_{EPOCH})$$

where T_{EPOCH} is the base epoch of the model, which for WMM-90 is 1990.0. Thus, $g_{nm}(T_{EPOCH})$ and $h_{nm}(T_{EPOCH})$ are the Gauss coefficients of the WMM at the model's base epoch, while $\dot{g}_{nm}$ and $\dot{h}_{nm}$ (pronounced g_{nm} dot and h_{nm} dot) are the annual rates of change of the Gauss coefficients. The Gauss coefficients $g_{nm}(T_{EPOCH})$ and $h_{nm}(T_{EPOCH})$ and their annual rates of change are spherical harmonic coefficients. The Gauss coefficients $g_{nm}(T_{EPOCH})$ and $h_{nm}(T_{EPOCH})$ characterize the Earth's main magnetic field at the base epoch of the model, T_{EPOCH} while $\dot{g}_{nm}$, and $\dot{h}_{nm}$ characterize the secular change of the Earth's main magnetic field during the 5-year life of the model. These coefficients, up to degree and order 12 comprise the WMM. Currently, the secular variation portion of the WMM is padded with zeros from degree 9 through degree 12.

30.4 <u>Geomagnetic components</u>. The Earth's magnetic field $\vec{B}(r,\theta,\phi,\tau)$ is a vector quantity having three components which correspond to the projection of the magnetic field vector onto the three coordinate axes. Thus, $B_r(r,\theta,\phi,\tau)$ is that portion of the field pointing in the radial direction (i.e., perpendicular to the surface of a spherical Earth), $B_\theta(r,\theta,\phi,\tau)$ is that portion of the field pointing locally due South, and $B_\phi(r,\theta,\phi,\tau)$ is that portion of the field pointing locally due East. The magnetic field vector can be computed from the geomagnetic potential by taking its gradient, thus:

$$\vec{B}(r,\theta,\phi,\tau) = - \vec{\nabla} V(r,\theta,\phi,\tau)$$

Consequently, the magnetic field components are related to the geomagnetic potential as follows:

$$B_r(r,\theta,\phi,\tau) = - \frac{\partial V(r,\theta,\phi,\tau)}{\partial r}$$

$$B_\theta(r,\theta,\phi,\tau) = -\ \frac{1}{r}\ \frac{\partial V(r,\theta,\phi,\tau)}{\partial\theta}$$

$$B_\phi(r,\theta,\phi,\tau) = -\ \frac{1}{r\sin\theta}\ \frac{\partial V(r,\theta,\phi,\tau)}{\partial\theta}$$

which yield the following spherical harmonic expansions:

$$B_r(r,\theta,\phi,\tau) = \sum_{n=1}^{N}(n+1)\left(\frac{R_E}{r}\right)^{n+2}\sum_{m=0}^{n}\left\{g_{nm}(\tau)\cos m\phi + h_{nm}(\tau)\sin m\phi\right\}P_n^m(\theta)$$

$$B_\theta(r,\theta,\phi,\tau) = -\ \sum_{n=1}^{N}\left(\frac{R_E}{r}\right)^{n+2}\sum_{m=0}^{n}\left\{g_{nm}(\tau)\cos m\phi + h_{nm}(\tau)\sin m\phi\right\}\frac{dP_n^m(\theta)}{d\theta}$$

$$B_\phi(r,\theta,\phi,\tau) = \frac{1}{\sin\theta}\sum_{n=1}^{N}\left(\frac{R_E}{r}\right)^{n+2}\sum_{m=0}^{n}m\left\{g_{nm}(\tau)\sin m\phi -\ h_{nm}(\tau)\cos m\phi\right\}P_n^m(\theta)$$

30.5 Coefficient normalization. It must be noted that the Gauss coefficients $g_{nm}(\tau)$ and $h_{nm}(\tau)$ as well as the associated Legendre polynomials and their derivatives, are Schmidt normalized by an international agreement (circa 1930) of the International Union of Geodesy and Geophysics. This particular normalization allows one to determine which terms of the spherical harmonic model are the most significant simply by a cursory inspection of the model coefficients. The Schmidt normalized associated Legendre polynomials $P_n^m(\theta)$ are related to the un-normalized associated Legendre Polynomials $P^{nm}(\theta)$ (note position of indices) by the following relation:

$$P_n^m(\theta) = S^{nm}P^{nm}(\theta)$$

The Schmidt normalization factors S^{nm} and the un-normalized associated Legendre Polynomials $P^{nm}(\theta)$ are computed via recursion relationships as follows:

$$P^{\infty}(\theta) = \ 1$$

$$P^{nm}(\theta) = \ \sin\theta P^{n-1,m-1}(\theta) \qquad\qquad m = n \neq 0$$

$$P^{nm}(\theta) = \ \cos\theta P^{n-1,m}(\theta) -\ K^{nm}P^{n-2,m}(\theta) \qquad\qquad m < n, n \geq 1$$

$$\frac{dP^{\infty}(\theta)}{d\theta} = \ 0$$

$$\frac{dP^{nm}(\theta)}{d\theta} = \sin\theta \frac{dP^{n-1,m}(\theta)}{d\theta} + \cos\theta P^{n-1,m-1}(\theta) \qquad ,m = n \neq 0$$

$$\frac{dP^{nm}(\theta)}{d\theta} = \cos\theta \frac{dP^{n-1,m}(\theta)}{d\theta} - \sin\theta P^{n-1,m}(\theta) - K^{nm} \frac{dP^{n-2,m}(\theta)}{d\theta} \qquad ,m \neq n, n \geq 1$$

where:

$$K^{nm} = \frac{(n-1)^2 - m^2}{(2n-1)(2n-3)}$$

and where it is understood that the undefined polynomials $P^{-1,0}(\theta)$ and $\frac{dP^{-1,0}}{d\theta}(\theta)$ are to be set equal to zero. Similarly,

$$S^{\infty} = 1$$

$$S^{\infty} = \left(\frac{2n-1}{n}\right) S^{n-1,0} \qquad ,n > 0$$

$$S^{nm} = \sqrt{\frac{(n-m+1)j}{n+m}} \; S^{n,m-1}, \qquad \left\{\begin{matrix} j = 2 & for & m = 1 \\ j = 1 & for & m > 1 \end{matrix}\right\}$$

Also, computed via recursion relations are the longitudinally dependent functions $\cos(m\phi)$ and $\sin(m\phi)$, which are computed as follows:

$$\sin(m\phi) = 0 \qquad ,m = 0$$

$$\cos(m\phi) = 1 \qquad ,m = 0$$

$$\sin(m\phi) = \sin(\phi)\cos(m-1)\phi + \cos(\phi)\sin(m-1)\phi \qquad ,m > 0$$

$$\cos(m\phi) = \cos(\phi)\cos(m-1)\phi - \sin(\phi)\sin(m-1)\phi \qquad ,m > 0$$

30.6 Coordinate transformations. GEOMAG is intended to compute various components of the geomagnetic field in a geodetic coordinate system that uses the WGS-84 ellipsoid as the reference ellipsoid. However, the mathematical analysis in the previous section is based on spherical coordinates. Consequently, some coordinate transformations are necessary. A three step procedure is required.

a. Convert the geodetic latitude, longitude, and altitude (λ, ϕ, h) to spherical coordinates (r, θ, ϕ).

b. Compute the magnetic field components $B_r(r,\theta,\phi,\tau)$, $B_\theta(r,\theta,\phi,\tau)$, and $B_\phi(r,\theta,\phi,\tau)$

c. Rotate the magnetic field components from spherical coordinates to geodetic coordinates yielding the magnetic field components $B_x(\lambda,\phi,h,\tau)$, $B_y(\lambda,\phi,h,\tau)$, and $B_z(\lambda,\phi,h,\tau)$ which are the projections of the magnetic field vector $\vec{B}(\lambda,\phi,h,\tau)$ onto the *X*-North, *Y*-East, and *Z*-vertically down coordinates of a local rectangular coordinate system defined by the tangent plane to the ellipsoid which is concentric about the WGS-84 reference ellipsoid but which encompasses the point (λ,ϕ,h).

The transformations in step (a) are as follows:

$$\cos\theta = \frac{\sin\lambda}{\sqrt{Q^2\cos^2\lambda + \sin^2\lambda}}$$

$$\sin\theta = \sqrt{1-\cos^2\theta}$$

where, if $\boldsymbol{a}$ and $\boldsymbol{b}$ are respectively the semi-major and semi-minor axes of the WGS-84 ellipsoid:

$$Q = \frac{h\sqrt{a^2-(a^2-b^2)\sin^2\lambda} \; + \; a^2}{h\sqrt{a^2-(a^2-b^2)\sin^2\lambda} \; + \; b^2}$$

Furthermore:

$$r^2 = h^2 + 2h\sqrt{a^2-(a^2-b^2)\sin^2\lambda} \; + \; \frac{a^4-(a^4-b^4)\sin^2\lambda}{a^2-(a^2-b^2)\sin^2\lambda}$$

The transformation in step (c) depends on the rotation angle α through which the magnetic field vector must be rotated in going from spherical, to geodetic coordinates. This rotation angle is defined through the following relations:

$$\cos\alpha = \left\{h + \sqrt{a^2\cos^2\lambda + b^2\sin^2\lambda}\right\}/r$$

$$\sin\alpha = (a^2-b^2)\cos\lambda\sin\lambda \,/\left\{r\sqrt{a^2\cos^2\lambda + b^2\sin^2\lambda}\right\}$$

$$\alpha = \lambda - \frac{\pi}{2} + \theta$$

Consequently, the components of the magnetic field vector in geodetic coordinates may be computed as follows:

$$B_x(\lambda,\phi,h,\tau) = -\cos\alpha B_\theta(r,\theta,\phi,\tau) - \sin\alpha B_r(r,\theta,\phi,\tau)$$

$$B_y(\lambda,\phi,h,\tau) = B_\phi(r,\theta,\phi,\tau)$$

$$B_z(\lambda,\phi,h,\tau) = \sin\alpha B_\theta(r,\theta,\phi,\tau) - \cos\alpha B_r(r,\theta,\phi,\tau)$$

From these rectangular components of the geomagnetic field, it is possible to construct all others. In particular, the following parameters may be computed:

$$B_H(\lambda,\phi,h,\tau) = \sqrt{B_X^2(\lambda,\phi,h,\tau) + B_Y^2(\lambda,\phi,h,\tau)} \qquad \text{(Horizontal Intensity)}$$

$$B_F(\lambda,\phi,h,\tau) = \sqrt{B_H^2(\lambda,\phi,h,\tau) + B_Z^2(\lambda,\phi,h,\tau)} \qquad \text{(Total Intensity)}$$

$$B_D(\lambda,\phi,h,\tau) = \tan^{-1}\left\{\frac{B_Y(\lambda,\phi,h,\tau)}{B_X(\lambda,\phi,h,\tau)}\right\} \qquad \text{(Declination)}$$

$$B_I(\lambda,\phi,h,\tau) = \tan^{-1}\left\{\frac{B_Z(\lambda,\phi,h,\tau)}{B_H(\lambda,\phi,h,\tau)}\right\} \qquad \text{(Inclination)}$$

The geomagnetic Grid Variation B_G is defined in terms of the magnetic Declination B_D, the geodetic latitudes λ and the geodetic longitude ϕ as follows:

$$B_G(\lambda,\phi,h,\tau) = \begin{Bmatrix} B_D - \phi & \lambda \geq 0 \\ B_D + \phi & \lambda < 0 \end{Bmatrix} \qquad \text{(Grid Variation)}$$

30.7 <u>GEOMAG algorithm</u>.

30.7.1 <u>Gauss coefficients</u>. The Gauss coefficients at the base epoch, T_{EPOCH} are stored in array $\boldsymbol{C}$ such that the lower half of array $\boldsymbol{C}$ is occupied by the even harmonic Gauss coefficients $g_{nm}(T_{EPOCH})$, while the upper half of array $\boldsymbol{C}$ is occupied by the odd harmonic Gauss coefficients $h_{nm}(T_{EPOCH})$. TABLE I illustrates the details of the storage scheme, which is equivalent to the following mathematical assignments:

$$C_{nm} = \begin{Bmatrix} g_{nm} & ,m \leq n \\ h_{m,n+1} & ,m > n \end{Bmatrix}$$

which implies that:

$$g_{nm} = C_{nm} \qquad ,m \le n$$

$$h_{nm} = C_{m-1,n} \qquad ,m \le n, m \ne 0$$

The annual rates of change of the Gauss coefficients are stored in array ***CD*** (which stands for $\dot{C}$) so that the lower half of array ***CD*** is occupied by the even harmonic coefficients $\dot{g}_{nm}$, while the upper half of the array is occupied by the odd harmonic coefficients $\dot{h}_{nm}$. TABLE II illustrates the details of the storage scheme for array ***CD***. It is essentially the same as TABLE I for array ***C*** and corresponds to the following mathematical assignments:

$$\dot{C}_{nm} = \begin{Bmatrix} \dot{g}_{nm} & ,m \le n \\ \dot{h}_{m,n+1} & ,m > n \end{Bmatrix}$$

which implies that:

$$\dot{g}_{nm} = \dot{C}_{nm} \qquad ,m \le n$$

$$\dot{h}_{nm} = \dot{C}_{m-1,n} \qquad ,m \le n, m \ne 0$$

30.7.2 <u>The 1990 model coefficients</u>. The numerical values of the Gauss coefficients at the base epoch and their corresponding annual rates of change for the WMM-90 geomagnetic model are listed in TABLE III. These numerical values are inserted into arrays ***C*** and ***CD*** through data statements. The base epoch of the model is also assigned through a data statement. In order to update the GEOMAG algorithm to a new epoch geomagnetic model such as WMM-95, it is only necessary to replace the data statements with the new model coefficients and the new base epoch.

30.7.3 <u>Parameter correspondences</u>. Important parameters in the GEOMAG routine and their mathematical correspondences are:

A ~ a = 6378.137 km
B ~ b = 6356.7523142 km
RE ~ R_E = 6371.2 km

TIME ~ τ

EPOCH ~ T_{EPOCH}

DT ~ $\tau - T_{EPOCH}$

ALT ~ h

SNORM(N,M) ~ S^{nm}

K(N,M) ~ K^{nm}

GLAT ~ λ

GLON ~ ϕ

SP(M) ~ $\sin(m\phi)$

CP(M) ~ $\cos(m\phi)$

ST ~ $\sin(\theta)$

CT ~ $\cos(\theta)$

CA ~ $\cos(\alpha)$

SA ~ $\sin((\alpha)$

BR ~ B_r

BT ~ B_θ

BP ~ B_ϕ

BX ~ B_X

BY ~ B_Y

BZ ~ B_Z

BH ~ B_H

DEC ~ B_D

DIP ~ B_I

TI ~ B_F

G ~ B_G

MAXDEG ~ N

MAXORD ~ $M=N$

P(N,M) ~ P^{nm}

DP(N,M) ~ $\dfrac{dP^{nm}\theta}{d\theta}$

TC ~ $C+(\tau-T_{EPOCH})\dot{C}$

CD ~ $\dot{C}$

Q2 ~ Q^2

Note that R_E is not intended to be the mean radius of the WGS-84 ellipsoid. It is the mean radius of a modified IAU-66 ellipsoid.

30.7.4 GEOMAG organization and usage. The GEOMAG algorithm is organized into two modules, each with its own entry point. The first is an Initialization Module. Its purpose is to compute all constants such as the recursion relation factors for the associated Legendre polynomials K^{nm}, the Schmidt normalization factors S^{nm}, and any other parameters that do not depend on position or time. The entry point for this module is GEOMAG (MAXDEG). The parameter MAXDEG determines the maximum degree and order of the magnetic model to be used in the computations. Normally, MAXDEG = 12, which is the maximum degree and order of the WMM series geomagnetic models. In order to reduce computation time, MAXDEG may be set to a number less than 12 (e.g., 8 or 10).

However, the accuracy of the computed magnetic parameters is correspondingly reduced. MAXDEG must be set in the calling program. The second module is the Processing Module which has the entry point:

GEOMG1 (ALT, GLAT, GLON, TIME, DEC, DIP, TI, G)

The purpose of this module is to compute the magnetic declination, inclination, total intensity, and grid variation of each geodetic position and time supplied to it. The units of the parameters in the argument list of the GEOMG1 entry point are as follows:

ALT ~ kilometers (e.g.. 5.314)	(In)
GLAT ~ degrees (e.g.. 33.716)	(In)
GLON ~ degrees (e.g.. -163.315)	(In)
TIME ~ years (e.g.. 1992.427)	(In)
DEC ~ degrees (e.g.. -121.734)	(Out)
DIP ~ degrees (e.g.. 48.387)	(Out)
TI ~ nanoteslas (e.g. 35781.7)	(Out)
G ~ degrees (e.g. 51.768)	(Out)

The computed magnetic field parameters are referenced to the WGS-84 ellipsoid. The last parameter, G, is the grid variation which is computed only in the polar regions (i.e., above + 55° latitude or below - 55° latitude). Outside of this region, a value of -999.0 is dummied in. It is referenced to grid north of a polar stereographic projection. The Model is considered valid at altitudes ranging from -100 km to 1000 km.

TABLE I. Arrangement of main field coefficients in array C_{nm}

n/m	0	1	2	3	4	5	6	7	8	9	10	11	12
0	g_{00}	h_{11}	h_{21}	h_{31}	h_{41}	h_{51}	h_{66}	h_{71}	h_{81}	h_{91}	$h_{10,1}$	$h_{11,1}$	$h_{12,1}$
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2	g_{20}	g_{21}	g_{22}	h_{33}	h_{43}	h_{53}	h_{63}	h_{73}	h_{83}	h_{93}	$h_{10,3}$	$h_{11,3}$	$h_{12,3}$
3	g_{30}	g_{31}	g_{32}	g_{33}	h_{44}	h_{54}	h_{64}	h_{74}	h_{84}	h_{94}	$h_{10,4}$	$h_{11,4}$	$h_{12,4}$
4	g_{40}	g_{41}	g_{42}	g_{43}	g_{44}	h_{55}	h_{65}	h_{75}	h_{85}	h_{95}	$h_{10,5}$	$h_{11,5}$	$h_{12,5}$
5	g_{50}	g_{51}	g_{52}	g_{53}	g_{54}	g_{55}	h_{66}	h_{76}	h_{86}	h_{96}	$h_{10,6}$	$h_{11,6}$	$h_{12,6}$
6	g_{60}	g_{61}	g_{62}	g_{63}	g_{64}	g_{65}	g_{66}	h_{77}	h_{87}	h_{97}	$h_{10,7}$	$h_{11,7}$	$h_{12,7}$
7	g_{70}	g_{71}	g_{72}	g_{73}	g_{74}	g_{75}	g_{76}	g_{77}	h_{88}	h_{98}	$h_{10,8}$	$h_{11,8}$	$h_{12,8}$
8	g_{80}	g_{81}	g_{82}	g_{83}	g_{84}	g_{85}	g_{86}	g_{87}	g_{88}	h_{99}	$h_{10,9}$	$h_{11,9}$	$h_{12,9}$
9	g_{90}	g_{91}	g_{92}	g_{93}	g_{94}	g_{95}	g_{96}	g_{97}	g_{98}	g_{99}	$h_{10,10}$	$h_{11,10}$	$h_{12,10}$
10	$g_{10,0}$	$g_{10,1}$	$g_{10,2}$	$g_{10,3}$	$g_{10,4}$	$g_{10,5}$	$g_{10,6}$	$g_{10,7}$	$g_{10,8}$	$g_{10,9}$	$g_{10,10}$	$h_{11,11}$	$h_{12,11}$
11	$g_{11,0}$	$g_{11,1}$	$g_{11,2}$	$g_{11,3}$	$g_{11,4}$	$g_{11,5}$	$g_{11,6}$	$g_{11,7}$	$g_{11,8}$	$g_{11,9}$	$g_{11,10}$	$g_{11,11}$	$h_{12,12}$
12	$g_{12,0}$	$g_{12,1}$	$g_{12,2}$	$g_{12,3}$	$g_{12,4}$	$g_{12,5}$	$g_{12,6}$	$g_{12,7}$	$g_{12,8}$	$g_{12,9}$	$g_{12,10}$	$g_{12,11}$	$g_{12,12}$

TABLE II. Arrangement of main field coefficients in array $\dot{C}_{nm}$

n/m	0	1	2	3	4	5	6	7	8	9	10	11	12
0	$\dot{g}_{00}$	$\dot{h}_{11}$	$\dot{h}_{21}$	$\dot{h}_{31}$	$\dot{h}_{41}$	$\dot{h}_{51}$	$\dot{h}_{66}$	$\dot{h}_{71}$	$\dot{h}_{81}$	$\dot{h}_{91}$	$\dot{h}_{10,1}$	$\dot{h}_{11,1}$	$\dot{h}_{12,1}$
1	$\dot{g}_{10}$	$\dot{g}_{11}$	$\dot{h}_{22}$	$\dot{h}_{32}$	$\dot{h}_{42}$	$\dot{h}_{52}$	$\dot{h}_{62}$	$\dot{h}_{72}$	$\dot{h}_{82}$	$\dot{h}_{92}$	$\dot{h}_{10,2}$	$\dot{h}_{11,1}$	$\dot{h}_{12,2}$
2	$\dot{g}_{20}$	$\dot{g}_{21}$	$\dot{g}_{22}$	$\dot{h}_{33}$	$\dot{h}_{43}$	$\dot{h}_{53}$	$\dot{h}_{63}$	$\dot{h}_{73}$	$\dot{h}_{83}$	$\dot{h}_{93}$	$\dot{h}_{10,3}$	$\dot{h}_{11,3}$	$\dot{h}_{12,3}$
3	$\dot{g}_{30}$	$\dot{g}_{31}$	$\dot{g}_{32}$	$\dot{g}_{33}$	$\dot{h}_{44}$	$\dot{h}_{54}$	$\dot{h}_{64}$	$\dot{h}_{74}$	$\dot{h}_{84}$	$\dot{h}_{94}$	$\dot{h}_{10,4}$	$\dot{h}_{11,4}$	$\dot{h}_{12,4}$
4	$\dot{g}_{40}$	$\dot{g}_{41}$	$\dot{g}_{42}$	$\dot{g}_{43}$	$\dot{g}_{44}$	$\dot{h}_{55}$	$\dot{h}_{65}$	$\dot{h}_{75}$	$\dot{h}_{85}$	$\dot{h}_{95}$	$\dot{h}_{10,5}$	$\dot{h}_{11,5}$	$\dot{h}_{12,5}$
5	$\dot{g}_{50}$	$\dot{g}_{51}$	$\dot{g}_{52}$	$\dot{g}_{53}$	$\dot{g}_{54}$	$\dot{g}_{55}$	$\dot{h}_{66}$	$\dot{h}_{76}$	$\dot{h}_{86}$	$\dot{h}_{96}$	$\dot{h}_{10,6}$	$\dot{h}_{11,6}$	$\dot{h}_{12,6}$
6	$\dot{g}_{60}$	$\dot{g}_{61}$	$\dot{g}_{62}$	$\dot{g}_{63}$	$\dot{g}_{64}$	$\dot{g}_{65}$	$\dot{g}_{66}$	$\dot{h}_{77}$	$\dot{h}_{87}$	$\dot{h}_{97}$	$\dot{h}_{10,7}$	$\dot{h}_{11,7}$	$\dot{h}_{12,7}$
7	$\dot{g}_{70}$	$\dot{g}_{71}$	$\dot{g}_{72}$	$\dot{g}_{73}$	$\dot{g}_{74}$	$\dot{g}_{75}$	$\dot{g}_{76}$	$\dot{g}_{77}$	$\dot{h}_{88}$	$\dot{h}_{98}$	$\dot{h}_{10,8}$	$\dot{h}_{11,8}$	$\dot{h}_{12,8}$
8	$\dot{g}_{80}$	$\dot{g}_{81}$	$\dot{g}_{82}$	$\dot{g}_{83}$	$\dot{g}_{84}$	$\dot{g}_{85}$	$\dot{g}_{86}$	$\dot{g}_{87}$	$\dot{g}_{88}$	$\dot{h}_{99}$	$\dot{h}_{10,9}$	$\dot{h}_{11,9}$	$\dot{h}_{12,9}$
9	$\dot{g}_{90}$	$\dot{g}_{91}$	$\dot{g}_{92}$	$\dot{g}_{93}$	$\dot{g}_{94}$	$\dot{g}_{95}$	$\dot{g}_{96}$	$\dot{g}_{97}$	$\dot{g}_{98}$	$\dot{g}_{99}$	$\dot{h}_{10,10}$	$\dot{h}_{11,10}$	$\dot{h}_{12,10}$
10	$\dot{g}_{10,0}$	$\dot{g}_{10,1}$	$\dot{g}_{10,2}$	$\dot{g}_{10,3}$	$\dot{g}_{10,4}$	$\dot{g}_{10,5}$	$\dot{g}_{10,6}$	$\dot{g}_{10,7}$	$\dot{g}_{10,8}$	$\dot{g}_{10,9}$	$\dot{g}_{10,10}$	$\dot{h}_{11,11}$	$\dot{h}_{12,11}$
11	$\dot{g}_{11,0}$	$\dot{g}_{11,1}$	$\dot{g}_{11,2}$	$\dot{g}_{11,3}$	$\dot{g}_{11,4}$	$\dot{g}_{11,5}$	$\dot{g}_{11,6}$	$\dot{g}_{11,7}$	$\dot{g}_{11,8}$	$\dot{g}_{11,9}$	$\dot{g}_{11,10}$	$\dot{g}_{11,11}$	$\dot{h}_{12,12}$
12	$\dot{g}_{12,0}$	$\dot{g}_{12,1}$	$\dot{g}_{12,2}$	$\dot{g}_{12,3}$	$\dot{g}_{12,4}$	$\dot{g}_{12,5}$	$\dot{g}_{12,6}$	$\dot{g}_{12,7}$	$\dot{g}_{12,8}$	$\dot{g}_{12,9}$	$\dot{g}_{12,10}$	$\dot{g}_{12,11}$	$\dot{g}_{12,12}$

TABLE III. WMM-90 Schmidt normalized gauss coefficients.

n	m	g_{nm}	h_{nm}	$\dot{g}_{nm}$	$\dot{h}_{nm}$
1	0	-29780.5	.0	16.0	.0
1	1	-1851.7	5407.2	9.3	-13.8
2	0	-2134.3	.0	-11.7	.0
2	1	3062.2	-2278.3	3.7	-12.8
2	2	1691.9	-384.3	1.8	-14.9
3	0	1312.9	.0	2.1	.0
3	1	-2244.7	-284.9	-7.6	3.1
3	2	1246.8	291.7	.0	.8
3	3	808.6	-352.4	-5.8	-11.3
4	0	933.5	.0	-.8	.0
4	1	784.9	249.4	1.0	3.3
4	2	323.5	-232.7	-7.4	3.7
4	3	-421.7	91.3	.8	2.8
4	4	139.2	-296.5	-6.4	.0
5	0	-208.3	.0	1.7	.0
5	1	352.2	40.8	.0	.0
5	2	246.5	148.7	.0	-2.1
5	3	-110.8	-154.6	-2.7	1.2
5	4	-162.3	-67.6	.0	1.2
5	5	-37.2	97.4	3.0	.6
6	0	59.0	.0	.8	.0
6	1	63.7	-14.7	.0	-.6
6	2	60.0	82.2	1.5	-.6
6	3	-181.3	70.0	.0	.0
6	4	.4	-56.2	.0	-2.3
6	5	15.4	-1.4	.0	.0
6	6	-96.0	24.6	.0	.0
7	0	76.1	.0	.5	.0
7	1	-62.1	-78.6	.0	.6
7	2	1.3	-26.7	-.9	.8
7	3	30.2	.1	1.5	.0
7	4	4.7	19.9	2.7	.0
7	5	7.9	17.9	-1.0	.0
7	6	10.1	-21.5	.0	.4
7	7	1.9	-6.8	.0	.0
8	0	22.9	.0	.0	.0
8	1	2.3	9.7	-1.1	.4
8	2	-1.2	-19.3	.0	-.8
8	3	-11.7	6.6	.0	.5
8	4	-17.5	-20.1	-2.1	.3
8	5	2.2	13.4	.0	.5
8	6	5.7	9.8	1.0	.0
8	7	3.0	-19.0	.0	-.7
8	8	-7.0	-9.1	.0	.0

TABLE III. WMM-90 Schmidt normalized gauss coefficients-Continued.

n	m	g_{nm}	h_{nm}	$\dot{g}_{nm}$	$\dot{h}_{nm}$
9	0	3.6	.0	.0	.0
9	1	9.5	-21.9	.0	.0
9	2	-.9	14.3	.0	.0
9	3	-10.7	9.5	.0	.0
9	4	10.7	-6.7	.0	.0
9	5	-3.2	-6.4	.0	.0
9	6	-1.4	9.1	.0	.0
9	7	6.3	8.9	.0	.0
9	8	.8	-8.0	.0	.0
9	9	-5.5	2.1	.0	.0
10	0	-3.3	.0	.0	.0
10	1	-2.6	2.6	.0	.0
10	2	4.5	1.2	.0	.0
10	3	-5.6	2.6	.0	.0
10	4	-3.6	5.7	.0	.0
10	5	3.9	-4.0	.0	.0
10	6	3.2	-.4	.0	.0
10	7	1.7	-1.7	.0	.0
10	8	3.0	3.8	.0	.0
10	9	3.7	-.8	.0	.0
10	10	.7	-6.5	.0	.0
11	0	1.3	.0	.0	.0
11	1	-1.4	.0	.0	.0
11	2	-2.5	1.0	.0	.0
11	3	3.2	-1.6	.0	.0
11	4	.2	-2.2	.0	.0
11	5	-1.1	1.1	.0	.0
11	6	.3	-.7	.0	.0
11	7	-.3	-1.7	.0	.0
11	8	.9	-1.5	.0	.0
11	9	-1.1	-1.3	.0	.0
11	10	2.4	-1.1	.0	.0
11	11	3.0	.6	.0	.0
12	0	-1.3	.0	.0	.0
12	1	.1	.7	.0	.0
12	2	.5	7	.0	.0
12	3	.7	1.3	.0	.0
12	4	.4	-1.5	.0	.0
12	5	-.2	.3	.0	.0
12	6	-1.1	.2	.0	.0
12	7	.9	-1.1	.0	.0
12	8	-.6	1.2	.0	.0
12	9	.8	-.2	.0	.0
12	10	.2	-1.3	.0	.0
12	11	.4	.6	.0	.0
12	12	.2	6	.0	.0

30.8 Algorithm.

```
C*****************************************************************
C
C
C      SUBROUTINE GEOMAG (GEOMAGNETIC FIELD COMPUTATION)
C
C
C*****************************************************************
C
C
C    WMM-90 is a Defense Mapping Agency (DMA) standard product.
C    For information on the use and applicability of this
C    product contact
C
C         DIRECTOR
C         DEFENSE MAPPING AGENCY
C         ATTN: PR, ST A-13
C         8613 LEE HIGHWAY
C         FAIRFAX, VA 22031-2137
C
C
C*****************************************************************
C
C    GEOMAG PROGRAMMED BY:
C
C            JOHN M. QUINN  7/19/90
C            GEOPOTENTIAL DIVISION, CODE GGA
C            U.S. NAVAL OCEANOGRAPHIC OFFICE
C            STENNIS SPACE CENTER, MS 39522-5001
C            PHONE: COMM  (601) 688-4264
C            DSN:  485-4264
C            FAX:  (601) 688-5701
C
C
C*****************************************************************
C
C
C   PURPOSE: THIS ROUTINE COMPUTES THE DECLINATION (DEC),
C            INCLINATION (DIP), TOTAL INTENSITY (TI) AND GRID
C            VARIATION (GV - POLAR REGIONS USING A POLAR
C            STEREOGRAPHIC PROJECTION ONLY) OF THE EARTH'S
C            MAGNETIC FIELD IN GEODETIC COORDINATES FROM THE
C            COEFFICIENTS OF THE CURRENT OFFICIAL DEPARTMENT
C            OF DEFENSE (DOD) SPHERICAL HARMONIC WORLD
C            MAGNETIC MODEL (WMM-90). THE WMM SERIES OF MODELS
C            IS UPDATED EVERY 5 YEARS ON 1 JANUARY OF THOSE
C            YEARS WHICH ARE DIVISIBLE BY 5 (I.E. 1980, 1985,
C            1990 ETC.) BY THE U.S. NAVAL OCEANOGRAPHIC
C            OFFICE IN COOPERATION WITH THE BRITISH GEOLOGICAL
C            SURVEY (BGS) AND IS BASED ON GEOMAGNETIC SURVEY
C            MEASUREMENTS FROM AIRCRAFT, SATELLITE, AND
C            GEOMAGNETIC OBSERVATORIES.
C*****************************************************************
```

```
C
C
C     MODEL:  THE WMM SERIES GEOMAGNETIC MODELS ARE COMPOSED
C             OF TWO PARTS:  THE MAIN FIELD MODEL, WHICH IS
C             VALID AT THE BASE EPOCH OF THE CURRENT MODEL AND
C             A SECULAR VARIATION MODEL, WHICH ACCOUNTS FOR SLOW
C             TEMPORAL VARIATIONS IN THE MAIN GEOMAGNETIC FIELD
C             FROM THE BASE EPOCH TO A MAXIMUM OF 5 YEARS BEYOND
C             THE BASE EPOCH.  FOR EXAMPLE, THE BASE EPOCH OF
C             THE WMM-90 MODEL IS 1990.0. THIS MODEL IS THEREFORE
C             CONSIDERED VALID BETWEEN 1990.0 AND 1995.0. THE
C             COMPUTED MAGNETIC PARAMETERS ARE REFERENCED TO THE
C             WGS-84 ELLIPSOID.
C
C
C*************************************************************
C
C
C ACCURACY:  IN OCEAN AREAS AT THE EARTH'S
C             SURFACE OVER THE ENTIRE 5-YEAR LIFE OF A
C             DEGREE AND ORDER 12 SPHERICAL HARMONIC MODEL
C             SUCH AS WMM-90, THE RMS DECLINATION ERROR IS
C             ESTIMATED TO BE < 1.0 DEGREES, AND THE RMS
C             INCLINATION ERROR IS ESTIMATED TO BE < 1.0
C             DEGREES. ALSO, THE RMS HORIZONTAL INTENSITY
C             AND VERTICAL COMPONENT ERRORS ARE ESTIMATED
C             TO BE < 200 NANOTESLAS.
C
C             THE ACCURACY AT ANY GIVEN TIME OF ALL FOUR
C             GEOMAGNETIC PARAMETERS DEPENDS ON THE
C             GEOMAGNETIC LATITUDE. THE ERRORS ARE LEAST AT
C             THE EQUATOR AND GREATEST AT THE MAGNETIC
C             POLES.
C
C             IT IS VERY IMPORTANT TO NOTE THAT A DEGREE AND
C             ORDER 12 MODEL, SUCH AS WMM-90, DESCRIBES
C             ONLY THE LONG WAVELENGTH SPATIAL MAGNETIC
C             FLUCTUATIONS DUE TO EARTH'S CORE. NOT
C             INCLUDED IN THE WMM SERIES MODELS ARE
C             INTERMEDIATE AND SHORT WAVELENGTH SPATIAL
C             FLUCTUATIONS OF THE GEOMAGNETIC FIELD WHICH
C             ORIGINATE IN THE EARTH'S MANTLE AND CRUST.
C             CONSEQUENTLY, ISOLATED ANGULAR RESIDUALS AT
C             VARIOUS POSITIONS ON THE SURFACE (PRIMARILY
C             OVER LAND, IN CONTINENTAL MARGINS, AND OVER
C             OCEANIC SEAMOUNTS, RIDGES, AND TRENCHES) OF
C             SEVERAL DEGREES MAY BE EXPECTED. ALSO NOT
C             INCLUDED IN THE MODEL ARE NONSECULAR TEMPORAL
C             FLUCTUATIONS OF THE GEOMAGNETIC FIELD OF
C             MAGNETOSPHERIC AND IONOSPHERIC ORIGIN. DURING
C             MAGNETIC STORMS, TEMPORAL FLUCTUATIONS CAN
C             CAUSE SUBSTANTIAL DEVIATIONS OF THE
C             GEOMAGNETIC FIELD FROM MODEL VALUES. IN
C             ARCTIC AND ANTARCTIC REGIONS, AS WELL AS IN
```

```
C             EQUATORIAL REGIONS, DEVIATIONS FROM MODEL
C             VALUES ARE BOTH FREQUENT AND PERSISTENT.
C
C             IF THE REQUIRED DECLINATION ACCURACY IS MORE
C             STRINGENT THAN THE WMM SERIES OF MODELS
C             PROVIDE, THE USER IS ADVISED TO REQUEST
C             SPECIAL (REGIONAL OR LOCAL) SURVEYS BE
C             PERFORMED AND MODELS PREPARED BY NAVOCEANO,
C             WHICH OPERATES THE PROJECT MAGNET AIRCRAFT
C             AND THE POLAR ORBITING GEOMAGNETIC SURVEY
C             (POGS) SATELLITE.  REQUESTS OF THIS NATURE
C             SHOULD BE MADE THROUGH THE OCEANOGRAPHER OF
C             THE NAVY (CNO OP-096) AT THE FOLLOWING
C             ADDRESS:
C
C                          OCEANOGRAPHER OF THE NAVY
C                          US NAVAL OBSERVATORY
C                          34TH AND MASSACHUSETTS AVE., NW
C                          WASHINGTON, DC  20392-5105
C
C
C*****************************************************************
C
C
C          USAGE:   THIS ROUTINE IS DIVIDED INTO TWO PARTS:
C
C          A)  AN INITIALIZATION MODULE, WHICH IS CALLED
C              ONLY ONCE AT THE BEGINNING OF THE MAIN
C              (CALLING) PROGRAM
C
C          B)  A PROCESSING MODULE, WHICH COMPUTES THE
C              MAGNETIC FIELD PARAMETERS FOR EACH
C              SPECIFIED GEODETIC POSITION (ALTITUDE,
C              LATITUDE, LONGITUDE) AND TIME
C
C          INITIALIZATION IS MADE VIA A SINGLE CALL TO THE MAIN
C          ENTRY POINT (GEOMAG), WHILE SUBSEQUENT PROCESSING
C          CALLS ARE MADE THROUGH THE SECOND ENTRY POINT
C          (GEOMG1). ONE CALL TO THE PROCESSING MODULE IS
C          REQUIRED FOR EACH POSITION AND TIME.
C
C          THE VARIABLE MAXDEG IN THE INITIALIZATION CALL IS THE
C          MAXIMUM DEGREE TO WHICH THE SPHERICAL HARMONIC MODEL
C          IS TO BE COMPUTED. IT MUST BE SPECIFIED BY THE USER IN
C          THE CALLING ROUTINE. NORMALLY IT IS 12 BUT IT MAY BE
C          SET LESS THAN 12 TO INCREASE COMPUTATIONAL SPEED AT
C          THE EXPENSE OF REDUCED ACCURACY.
C
C          THE PC VERSION OF THIS SUBROUTINE MUST BE COMPILED
C          WITH A FORTRAN 77 COMPATIBLE COMPILER SUCH AS THE
C          MICROSOFT OPTIMIZING FORTRAN COMPILER VERSION 4.1 OR
C          LATER.
C
C
```

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C*****************************************************************
C
C
C        REFERENCES:
C
C        JOHN M. QUINN, DAVID J. KERRIDGE, AND DAVID R.
C           BARRACLOUGH; WORLD MAGNETIC CHARTS FOR 1985 -
C           SPHERICAL HARMONIC MODELS OF THE GEOMAGNETIC FIELD
C           AND ITS SECULAR VARIATION, GEOPHYS. J. R. ASTR. SOC.
C           (1986) Vol. 87, PP. 1143-1157
C
C        DEFENSE MAPPING AGENCY TECHNICAL REPORT, TR 8350.2:
C           DEPARTMENT OF DEFENSE WORLD GEODETIC SYSTEM 1984,
C           SEPT. 30 (1987)
C
C        JOSEPH C. CAIN, ET AL., A PROPOSED MODEL FOR THE
C           INTERNATIONAL GEOMAGNETIC REFERENCE FIELD - 1965,
C           J. GEOMAG. AND GEOELECT. VOL. 19, NO. 4, PP. 335-355
C           (1967) (SEE APPENDIX)
C
C        ALFRED J. ZMUDA, WORLD MAGNETIC SURVEY 1957-1969,
C           INTERNATIONAL ASSOCIATION OF GEOMAGNETISM AND
C           AERONOMY (IAGA) BULLETIN #28, PP. 186-188 (1971)
C
C
C*****************************************************************
C
C
C      PARAMETER DESCRIPTIONS:
C
C    A        - SEMIMAJOR AXIS OF WGS-84 ELLIPSOID (KM)
C    B        - SEMIMINOR AXIS OF WGS-84 ELLIPSOID (KM)
C    RE       - MEAN RADIUS OF IAU-66 ELLIPSOID (KM)
C    SNORM    - SCHMIDT NORMALIZATION FACTORS
C    C        - GAUSS COEFFICIENTS OF MAIN GEOMAGNETIC MODEL (NT)
C    CD       - GAUSS COEFFICIENTS OF SECULAR GEOMAGNETIC MODEL (NT/yR)
C    TC       - TIME ADJUSTED GEOMAGNETIC GAUSS COEFFICIENTS (NT)
C    OTIME    - TIME ON PREVIOUS CALL TO GEOMAG (YRS)
C    OALT     - GEODETIC ALTITUDE ON PREVIOUS CALL TO GEOMAG (YRS)
C    OLAT     - GEODETIC LATITUDE ON PREVIOUS CALL
C                 TO GEOMAG (DEG.)
C    OLON     - GEODETIC LONGITUDE ON PREVIOUS CALL TO GEOMAG (DEG.)
C    TIME     - COMPUTATION TIME (YRS)                        (INPUT)
C                 (E.G., 1 JULY 1985 = 1985.500)
C    ALT      - GEODETIC ALTITUDE (KM)                        (INPUT)
C    GLAT     - GEODETIC LATITUDE (DEG.)                      (INPUT)
C    GLON     - GEODETIC LONGITUDE (DEG.)                     (INPUT)
C    EPOCH    - BASE TIME OF GEOMAGNETIC MODEL (YRS)
C    DTR      - DEGREE TO RADIAN CONVERSION
C    SP(M)    - SINE OF (M*SPHERICAL COORD. LONGITUDE)
C    CP(M)    - COSINE OF (M*SPHERICAL COORD. LONGITUDE)
C    ST       - SINE OF (SPHERICAL COORD. LATITUDE)
C    CT       - COSINE OF (SPHERICAL COORD. LATITUDE)
```

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C      R         - SPHERICAL COORDINATE RADIAL POSITION (KM)
C      CA        - COSINE OF SPHERICAL TO GEODETIC VECTOR ROTATION ANGLE
C      SA        - SINE OF SPHERICAL TO GEODETIC VECTOR ROTATION ANGLE
C      BR        - RADIAL COMPONENT OF GEOMAGNETIC FIELD (NT)
C      BT        - THETA COMPONENT OF GEOMAGNETIC FIELD (NT)
C      BP        - PHI COMPONENT OF GEOMAGNETIC FIELD (NT)
C      P(N,M)    - ASSOCIATED LEGENDRE POLYNOMIALS (UNNORMALIZED)
C      PP(N)     - ASSOCIATED LEGENDRE POLYNOMIALS FOR M=1 (UNNORMALIZED)
C      DP(N,M)   - THETA DERIVATIVE OF P(N,M) (UNNORMALIZED)
C      BX        - NORTH GEOMAGNETIC COMPONENT (NT)
C      BY        - EAST GEOMAGNETIC COMPONENT (NT)
C      BZ        - VERTICALLY DOWN GEOMAGNETIC COMPONENT (NT)
C      BH        - HORIZONTAL GEOMAGNETIC COMPONENT (NT)
C      DEC       - GEOMAGNETIC DECLINATION (DEG.)                (OUTPUT)
C                    EAST=POSITIVE ANGLES
C                    WEST=NEGATIVE ANGLES
C      DIP       - GEOMAGNETIC INCLINATION (DEG.)                (OUTPUT)
C                    DOWN=POSITIVE ANGLES
C                    UP=NEGATIVE ANGLES
C      TI        - GEOMAGNETIC TOTAL INTENSITY (NT)              (OUTPUT)
C      GV        - GEOMAGNETIC GRID VARIATION (DEG.)             (OUTPUT)
C                REFERENCED TO GRID NORTH
C                GRID NORTH REFERENCED TO 0 MERIDIAN OF A POLAR
C                STEREOGRAPHIC PROJECTION (ARCTIC/ANTARCTIC ONLY)
C      MAXDEG - MAXIMUM DEGREE OF SPHERICAL HARMONIC MODEL       (INPUT)
C      MOXORD - MAXIMUM ORDER OF SPHERICAL HARMONIC MODEL
C
C
C*****************************************************************
C
C
C   NOTE:  THIS VERSION OF GEOMAG USES THE WMM-90 GEOMAGNETIC
C          MODEL REFERENCED TO THE WGS-84 GRAVITY MODEL ELLIPSOID
C
C
C*****************************************************************
C
C
C
C
C
C
C
C
C*****************************************************************
C
C
C                    INITIALIZATION MODULE
C
C
C*****************************************************************
C
C
      SUBROUTINE GEOMAG (MAXDEG)
```

```
C
C
        DIMENSION C(0:12,0:12),CD(0:12,0:12),TC(0:12,0:12)
        DIMENSION P(0:12,0:12),DP(0:12,0:12),SNORM(0:12,0:12)
        DIMENSION SP(0:12),CP(0:12),FN(0:12),FM(0:12),PP(0:12)
        REAL K(0:12,0:12)
        EQUIVALENCE (SNORM,P)
C
C
        DATA EPOCH/1990.0/
C
   DATA C/          0.0,   -29780.5,   -2134.3,   1312.9,    933.5,    -208.3,
*                  59.0,       76.1,      22.9,      3.6,     -3.3,       1.3,
*                  -1.3,     5407.2,   -1851.7,   3062.2,  -2244.7,     784.9,
*                 352.2,       63.7,     -62.1,      2.3,      9.5,      -2.6,
*                  -1.4,        0.1,   -2278.3,    384.3,   1691.9,    1246.8,
*                 323.5,      246.5,      60.0,      1.3,     -1.2,      -0.9,
*                   4.5,       -2.5,       0.5,   -284.9,    291.7,    -352.4,
*                 808.6,     -421.7,    -110.8,   -181.3,     30.2,     -11.7,
*                 -10.7,       -5.6,       3.2,      0.7,    249.4,    -232.7,
*                  91.3,     -296.5,     139.2,   -162.3,      0.4,       4.7,
*                 -17.5,       10.7,      -3.6,      0.2,      0.4,      40.8,
*                 148.7,     -154.6,      67.6,     97.4,    -37.2,      15.4,
*                   7.9,        2.2,      -3.2,      3.9,     -1.1,      -0.2,
*                 -14.7,       82.2,      70.0,    -56.2,     -1.4,      24.6,
*                 -96.0,       10.1,       5.7,     -1.4,      3.2,       0.3,
*                  -1.1,     -78.6,-     -26.7,      0.1,     19.9,      17.9,
*                 -21.5,       -6.8,       1.9,      3.0,      6.3,       1.7,
*                  -0.3,        0.9,       9.7,    -19.3,      6.6,     -20.1,
*                  13.4,        9.8,      19.0,     -9.1,     -7.0,       0.8,
*                   3.0,        0.9,      -0.6,    -21.9,     14.3,       9.5,
*                  -6.7,       -6.4,       9.1,      8.9,     -8.0,       2.1,
*                  -5.5,        3.7,      -1.1,      0.8,      2.6,       1.2,
*                   2.6,        5.7,      -4.0,     -0.4,     -1.7,       3.8,
*                  -0.8,       -6.5,       0.7,      2.4,      0.2,       0.0,
*                   1.0,       -1.6,      -2.2,      1.1,     -0.7,      -1.7,
*                  -1.5,       -1.3,      -1.1,      0.6,      3.0,       0.4,
*                   0.7,        0.7,       1.3,     -1.5,      0.3,       0.2,
*                  -1.1,        1.2,       0.2,     -1.3,      0.6,       0.6,
*                   0.2/
C
C
   DATA CD/       0.0,  16.0, -11.7,    2.1,  -0.8,    1.7,   0.8,   0.5,
*                 0.0,   0.0,   0.0,    0.0,   0.0,  -13.8,   9.3,   3.7,
*                -7.6,   1.0,   0.0,    0.0,   0.0,   -1.1,   0.0,   0.0,
*                 0.0,   0.0, -12.8,  -14.9,   1.8,    0.0,  -7.4,   0.0,
*                 1.5,  -0.9,   0.0,    0.0,   0.0,    0.0,   0.0,   3.1,
*                 0.8, -11.3,  -5.8,    0.8,  -2.7,    0.0,   1.5,   0.0,
*                 0.0,   0.0,   0.0,    0.0,   3.3,    3.7,   2.8,   0.0,
*                -6.4,   0.0,   0.0,    2.7,  -2.1,    0.0,   0.0,   0.0,
*                 0.0,   0.0,  -2.1,    1.2,   1.2,    0.6,   3.0,   0.0,
*                -1.0,   0.0,   0.0,    0.0,   0.0,    0.0,  -0.6,  -0.6,
*                 0.0,  -2.3,   0.0,    0.0,   0.0,    0.0,   1.0,   0.0,
*                 0.0,   0.0,   0.0,    0.6,   0.8,    0.0,   0.0,   0.0,
*                 0.4,   0.0,   0.0,    0.0,   0.0,    0.0,   1.0,   0.0,
*                 0.4,  -0.8,  0.05,    0.3,   0.5,    0.0,  -0.7,   0.0,
*           57  *0.0/
```

```
C
C
C
C
C
C        INITIALIZE CONSTANTS
C
C
      IF (MAXDEG .GT. 12) MAXDEG=12
      MAXORD=MAXDEG
      PI=3.14159265359
      DTR=PI/180.0
      SP(0)=0.
      CP(O)=1.
      P(0,0)=1.
      PP(0)=1.
      DP(0,0)=0.
      A=6378.137
      B=6356.7523142
      RE=6371.2
      A2=A**2
      B2=B**2
      C2=A2-B2
      A4=A2**2
      B4=B2**2
      C4=A4-B4
C
C
C     CONVERT SCHMIDT NORMALIZED GAUSS COEFFICIENTS TO
C     UNNORMALIZED
C
     SNORM(0,0)=1.
     DO 20 N=1,MAXORD
     SNORM(N,O)=SNORM(N-1,O)*FLOAT(2*N-1)/FLOAT(N)
     J=2
     DO 10 M=0,N
     K(N,M)=FLOAT((N-1)**2-M**2)/FLOAT((2*N-1)*(2*N-3))
     IF (M .GT. O) THEN
     FLNMJ=FLOAT((N-M+1)*J)/FLOAT(N+M)
     SNORM(N,M)=SNORM(N,M-1)*SQRT(FLNMJ)
     J=1
     C(M-1,N)=SNORM(N,M)*C(M-1,N)
     CD(M-1,N)=SNORM(N,M)*CD(M-1,N)
     ENDIF
     C(N,M)=SNORM(N,M)*C(N,M)
     CD(N,M)=SNORM(N,M)*CD(N,M)
 10  CONTINUE
     FN(N)=FLOAT(N+1)
     FM(N)=FLOAT(N)
 20  CONTINUE
 C
 C
```

```
      OTIME=-1000.
      OALT=-1000.
      OLAT=-1000.
      OLON=-1000.
C
          RETURN
C
C
C*****************************************************************
C
C
C                            PROCESSING MODULE
C
C
C*****************************************************************
C
C
          ENTRY GEOMG1(ALT,GLAT,GLON,TIME,DEC,DIP,TI,GV)
C
C
   DT=TIME-EPOCH
   IF (OTIME .LT. 0; .AND. (DT .LT. 0. .OR. DT .GT. 5.)) THEN
   PRINT *,'         '
   PRINT *,' WARNING - TIME EXTENDS BEYOND MODEL 5-YEAR LIFE SPAN'
   PRINT *,' CONTACT DMA FOR PRODUCT UPDATES:'
   PRINT *,'         '
   PRINT *,'           DEFENSE MAPPING AGENCY'
   PRINT *,'           ATTN: Code PRS, ST A-13'
   PRINT *,'           8613 LEE HIGHWAY'
   PRINT *,'           FAIRFAX, VA 22031-2137'
   PRINT *,'           (703)285-9240, AUTOVON 356-9240'
   PRINT *,'         '
   PRINT *,' EPOCH   = ',EPOCH
   PRINT *,' TIME    = ',TIME
   ENDIF
C
C
     RLON=GLON*DTR
     RLAT=GLAT*DTR
     SRLON=SIN(RLON)
     SRLAT=SIN(RLAT)
     CRLON=COS(RLON)
     CRLAT=COS(RLAT)
     SRLON2=SRLON**2
     SRLAT2=SRLAT**2
     CRLON2=CRLON**2
     CRLAT2=CRLAT**2
     SP(1)=SRLON
     CP(1)=CRLON
C
C         CONVERT FROM GEODETIC COORDS. TO SPHERICAL COORDS.
C
     IF (ALT .NE. OALT .OR. GLAT .NE. OLAT) THEN
     Q=SQRT(A2-C2*SRLAT2)
```

```
      Q1=ALT*Q
      Q2=((Q1+A2)/(Q1+B2))**2
      CT=SRLAT/SQRT(Q2*CRLAT2+SRLAT2)
      ST=SQRT(1.O-CT**2)
      R2=ALT**2+2.0*Q1+(A4-C4*SRLAT2)/Q**2
      R=SQRT(R2)
      D=SQRT(A2*CRLAT2+B2*SRLAT2)
      CA=(ALT+D)/R
      SA=C2*CRLAT*SRLAT/R*D)
      ENDIF
C
C
      IF (GLON .NE. OLON) THEN
      DO 40 M=2,MAXORD
      SP(M)=SP(1)*CP(M-1)+CP(1)*SP(M-1)
      CP(M)=CP(1)*CP(M-1)-SP(1)*SP(M-1)
   40 CONTINUE
      ENDIF
C
C
      AOR=RE/R
      AR=AOR**2
C
C
      BR=O.
      BT=0.
      BP=O.
      BPP=O.
C
C
      DO 70 N=1,MAXORD
      DO 60 M=0,N
C
C         COMPUTE UNNORMALIZED ASSOCIATED LEGENDRE POLYNOMIALS
C         AND DERIVATIVES VIA RECURSION RELATIONS
C
      IF (ALT .NE. OALT .OR. GLAT .NE. OLAT) THEN
      IF (N .EQ. M) THEN
      P(N,M)=ST*P(N-1,M-1)
      DP(N, M)=ST*DP(N-1,M-1)+CT*P(N-1,M-1)
      GO TO 50
      ENDIF
      IF (N .EQ. 1 .AND. M .EQ. 0) THEN
      P(N,M)=CT*P(N-1,M)
      DP(N, M)=CT*DP(N-1, M)-ST*P(N-1,M)
      GO TO 50
      ENDIF
      IF (N .GT. 1 .AND. N .NE. M) THEN
      IF (M .GT. N-2) P(N-2,M)=0.0
      IF (M . GT . N-2 ) DP (N-2, M) =0 . O
      P(N, M)=CT*P  (N-1,M)-K  (N,M)*P  (N-2,M)
      DP(N,M)=CT*DP(N-1,M)-ST*P(N-1,M)-K(N,M)*DP(N-2,M)
      ENDIF
      ENDIF
```

```
   50 CONTINUE
C
C          TIME ADJUST THE GAUSS COEFFICIENTS
C
      IF (TIME .NE. OTIME) THEN
      TC(N,M)=C(N,M)+DT*CD(N,M)
      IF (M .NE. O) THEN
      TC(M-1,N)=C(M-1,N)+DT*CD(M-1,N)
      ENDIF
      ENDIF
C
C          ACCUMULATE TERMS OF THE SPHERICAL HARMONIC EXPANSIONS
C
      PAR=AR*P(N,M)
      IF (M .EQ. O) THEN
      TEMP1=TC(N,M)*CP(M)
      TEMP2=TC(N,M)*SP(M)
      ELSE
      TEMP1=TC(N,M)*CP(M)+TC(M-1,N)*SP(M)
      TEMP2=TC(N,M)*SP(M)-TC(M-1,N)*CP(M)
      ENDIF
      BT=BT-AR*TEMP1*DP(N,M)
      BP=BP+FM(M)*TEMP2*PAR
      BR=BR+FN(N)*TEMP1*PAR
C
C          SPECIAL CASE:  NORTH/SOUTH GEOGRAPHIC POLES
C
      IF (ST .EQ. 0.0 .AND. M .EQ. 1) THEN
      IF (N .EQ. 1) THEN
      PP(N)=PP(N-1)
      ELSE
      PP(N)=CT*PP(N-1)-K(N,M)*PP(N-2)
      ENDIF
      PARP=AR*PP(N)
      BPP=BPP+FM(M)*TEMP2*PARP
      ENDIF
C
C
   60 CONTINUE
   70 CONTINUE
C
C
      IF (ST .EQ. 0.0) THEN
      BP=BPP
      ELSE
      BP=BP/ST
      ENDIF
C
C          ROTATE MAGNETIC VECTOR COMPONENTS FROM SPHERICAL TO
C          GEODETIC COORDINATES
C
      BX=-BT*CA-BR*SA
      BY=BP
      BZ=BT*SA-BR*CA
```

```
C
           COMPUTE DECLINATION (DEC), INCLINATION (DIP) AND
           TOTAL INTENSITY (TI)
C
      BH=SQRT(BX**2+BY**2)
      TI=SQRT(BH**2+BZ**2)
      DEC=ATAN2(BY,BX)/DTR
      DIP=ATAN2(BZ,BH)/DTR
C
C          COMPUTE MAGNETIC GRID VARIATION IF THE CURRENT
C          GEODETIC POSITION IS IN THE ARCTIC OR ANTARCTIC
C          (I.E. GLAT > +55 DEGREES OR GLAT < -55 DEGREES)
C
C          OTHERWISE, SET MAGNETIC GRID VARIATION TO -999.0
C
      GV=-999.0
      IF (ABS(GLAT) .GE. 55.) THEN
      IF (GLAT .GE. 0.) GV=DEC-GLON
      IF (GLAT .LT. 0.) GV=DEC+GLON
      IF (GV .GT. +180.) GV=GV-360.
      IF (GV .LT. -180.) GV=GV+360.
      ENDIF
C
C
      OTIME=TIME
      OALT=ALT
      OLAT=GLAT
      OLON=GLON
C
C
      RETURN
C
C
      END
```

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CONCLUDING MATERIAL

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(project MCGT-0068)

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I RECOMMEND A CHANGE:	1. DOCUMENT NUMBER MIL-W-89500	2. DOCUMENT DATE *(YYMMDD)* 930618

3. DOCUMENT TITLE
Military Specification for World Magnetic Model (WMM)

4. NATURE OF CHANGE *(Identify paragraph number and include proposed rewrite, if possible. Attach extra sheets as needed.)*

5. REASON FOR RECOMMENDATION

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